Effect of multi-point indentation on the bending strength of silicon nitride ceramic

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Machining is an unavoidable, and usually the final stage, process for the requirements of both dimensional control and surface quality control of fine ceramic components. Unfortunately, some surface and/or subsurface damage is frequently introduced during the machining. Since the performance and reliability of ceramic components may be influenced strongly by this machining damage, considerable research has been conducted over the past two decades to characterize the mechanical behavior of machining, see for example [1] and references therein.

The mechanism of material removal in machining of ceramics has been assumed to be related to the types of damage produced during indentation [2]. The relationships between the machining damage and the fracture strength of ceramics have also been studied [3–5] based on the existing indentation fracture mechanics theory, which was established by Lawn and co-workers [6–8]. However, there has been little effort devoted to the differences between the machining and the traditional indentation. In fact, the contact between the diamond abrasives and the material during machining should be considered as a dynamic multi-point indentation process, which may be rather different from the quasi-static single-point indentation, i.e., the traditional indentation process. Therefore, it is necessary to make an in-depth comparison between the mechanical responses of ceramics to the machining and to the traditional indentation. As a preparatory study, the present letter addresses this issue, observing the effect of quasi-static, rather than dynamic, multi-point indentation on the bending strength of a pressureless sintered silicon nitride (SSN) ceramic.

Test specimens had approximate dimensions of 4 mm wide × 3 mm thick × 36 mm long. All the surfaces of the specimens were ground using a diamond wheel and the edges of the tensile surface were chamfered slightly. Careful polishing was then carried out, with diamond paste, on the tensile surface of the specimen to produce an optical finish. Finally, all specimens were subjected to air annealing at 1000 °C for 1 h to eliminate the residual stresses generated by grinding and polishing.

The quasi-static multi-point indentation tests were performed with a specially-designed multi-point indenter, which was prepared by violently smashing a block of alumina ceramic into small pieces with irregular shapes and then binding these pieces onto a steel plate with epoxy resin. Fig. 1 shows schematically the contact between the specially-designed multi-point indenter and the test specimen. After being multi-point indented, specimens were broken at room temperature in three-point bending with a span of 30 mm and a cross-head speed of 0.5 mm min^{-1}.

For comparison, the room temperature bending strength of the Vickers-indented specimen was also measured as a function of the indentation load. The Vickers indentation tests were performed with a standard procedure.

In Fig. 2, the measured bending strength of the multi-point indented specimen, σ_f, is plotted as a function of the applied indentation load, P_m. The error bars in this plot represent standard deviations for five tests at each load. Clearly, this $\sigma_f - P_m$ curve can be divided into three regions. Region I is a lower load region where the bending strength is nearly constant, independent of the applied indentation load. Region II is a medium load region where the bending strength increases to a maximum with the increasing P_m. With a further increase in P_m, the bending strength tends to decrease gradually.

The strength behavior of the multi-point indented specimen, shown in Fig. 2, is rather different from that of the single-point indented specimen. The fracture-strength/indentation-load relationship for single-point indented specimen has been established by Chantikul *et al.* [9] based on indentation fracture mechanics [7]. For material with a flat crack-growth-resistance (*R*-curve) behavior, it was predicted [9] that plotting log fracture strength of indented
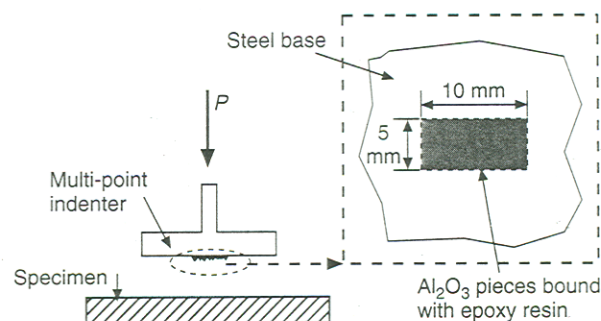

Figure 1 Schematic of the contact between the specially-designed multi-point indenter and the test specimen.
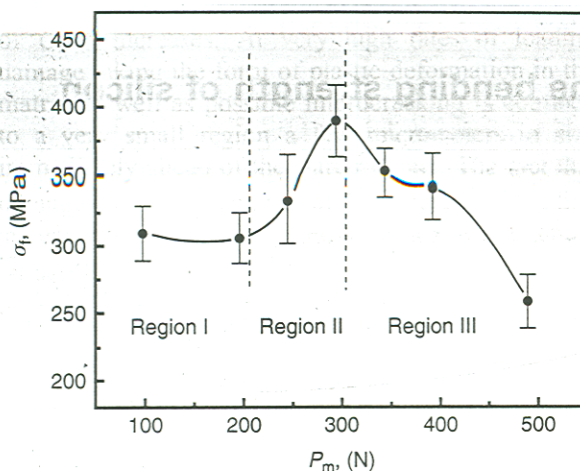
Figure 2 Measured bending strength of multi-point indented specimen as a function of the applied indentation load.

specimen versus log indentation load would yield a straight line with a slope of $-1/3$. Fig. 3 shows the measured bending strength of a Vickers indented specimen as a function of the applied indentation load, P_s. The slope of the fitting $\log \sigma_f - \log P_s$ line was determined to be -0.34, demonstrating that the experimental results are in good agreement with the theoretical prediction.

The differences between the strength behavior of the multi-point indented specimen and that of the single-point indented specimen can be understood by analyzing the deformation/fracture responses of the test material in each case.

In general, loading a "sharp" indenter or excessively loading a "blunt" indenter onto the surface of a brittle material may lead to the generation of a remnant plastic impression in the surface. Due to the elastic-plastic nature of such a contact, two types of surface/subsurface damage are frequently produced, one being residual stresses, which result from the mismatch between the plastically deformed zone beneath the impression and the surrounding elastic matrix, and the other being microcracking due to the higher stress concentration below the contact point. Microcracking usually results in a strength reduction, while the residual stresses also have a strong influence on the fracture strength [1].
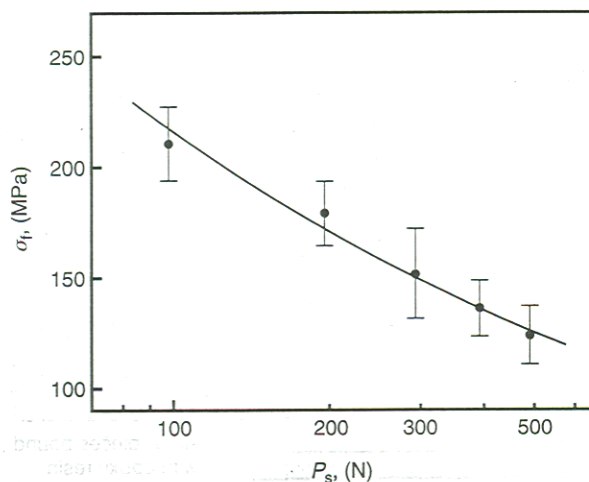
For single-point indentation, e.g., Vickers indentation, the size of the plastically deformed zone beneath the impression is usually much smaller than that of the so-called well-developed half-penny crack induced by Vickers indentation. As discussed by Lawn *et al.* [7], the residual stresses may manifest themselves as an extra driving force for crack propagation. Thus, the phenomenon shown in Fig. 3, i.e., the continuous decrease in the measured strength of Vickers indented specimen with increasing indentation load, can be understood easily.

For multi-point indentation, however, the effect of residual stresses on the strength of the indented specimen may be somewhat complex. In principle, the elastic-plastic interaction of the multi-point indenter with the ceramic surface can be considered analogous to that of a series of closely spaced, single-point indenters. Because the plastically deformed zones associated with each single-point indenter overlap one another, the complete contact surface, whose area is 5×10 mm^2 shown in Fig. 1, would be plastically deformed and in a state of compression [10]. Undoubtedly, such a surface residual stress may act as an extra resistance, rather than a driving force, for the propagation of the multi-point indentation induced microcracks during the subsequent breaking test, thereby resulting in an increase in fracture strength. Thus the $\sigma_f - P_m$ relation shown in Fig. 2 can be considered as a result of the competition between the effects of two different physical processes occurring during the multi-point indentation: the strength reduction due to microcracking and the strength enhancement due to surface residual stresses.

Although it seems to be impossible, at present, to make a quantitative discussion on the experimental results shown in Fig. 2, as there is still a lack of a suitable fracture mechanics model for the multi-point indentation, the fact that the measured $\sigma_f - P_m$ curve passes through a maximum may be expected to be useful for understanding the machining mechanism and optimizing the machining process. At least, the existence of the maximum in the measured $\sigma_f - P_m$ curve means that it may be possible to select a suitable machining force to obtain a minimum in strength reduction, if a similar phenomenon can also be observed from the dynamic, multi-point indentation experiments, i.e., the actual machining process. Clearly, this conclusion can not be deduced experimentally or theoretically based on the traditional single-point indentation.

Figure 3 Measured bending strength of Vickers indented specimen as a function of the applied indentation load.

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